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Application of subtractive clustering for power transformer fault diagnostics

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Abstract

The issue of developing methods and implementation of hardware and software for power transformer state control is relevant due to the need for enhancing stability and durability of essential expensive equipment. A promising diagnostic condition control technique for the high-voltage oil-filled electrical facilities is the method of positioning partial discharges (PDs) and their intense measuring. The paper provides outcome of experiments enabling acoustic PD positioning at the transformers of the power plant units. It considers the methods and algorithm of processing results of the periodical acoustic PD positioning based on the subtractive clustering technique. These methods provides a fault tracing and identification as well as assessment of their trend.

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1. Introduction

Implementation of means for fault diagnostics of oil-filled power transformers is challenging and highly urgent. This is due to a number of intrinsic reasons one of which is a physical equipment wear being as high as 50–70% in the Russian power sector. Furthermore, development of means and systems of technical diagnostics is the most essential condition of the Smart Grid technology introduction into the industrial electric networks [1-3].

One of the advanced and intensively developing methods of condition monitoring without deenergization (in on-line mode) is the partial discharge positioning. PDs have been recorded at the high-voltage facilities for diagnostics

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over the last 20 years. However, this method is used today mainly for monitoring power systems, large power plants and heavy-duty arc steel-making furnaces [4–6]. This fact may be explained by technical, research and methodical problems. One of substantial reasons is a lack of methods of transformer condition diagnostics based on processing and analyzing results of the periodic PD intense measurements.

2. Main part

We propose the engineering practice for identification of power transformer faults by analyzing complex partial discharge parameters. Fig. 1 shows the functional structure explaining the essence of the procedure developed.

It includes the following methods of mathematical analysis of PD parameters:

- analysis of PD intensity dependency upon the limit values;
- PD cluster analysis based on generation of uniform characteristics of the power equipment condition;
- amplitude and phase analysis of the time-dependent behavior of PD signals;
- spectrum analysis of harmonic content of PD signals.

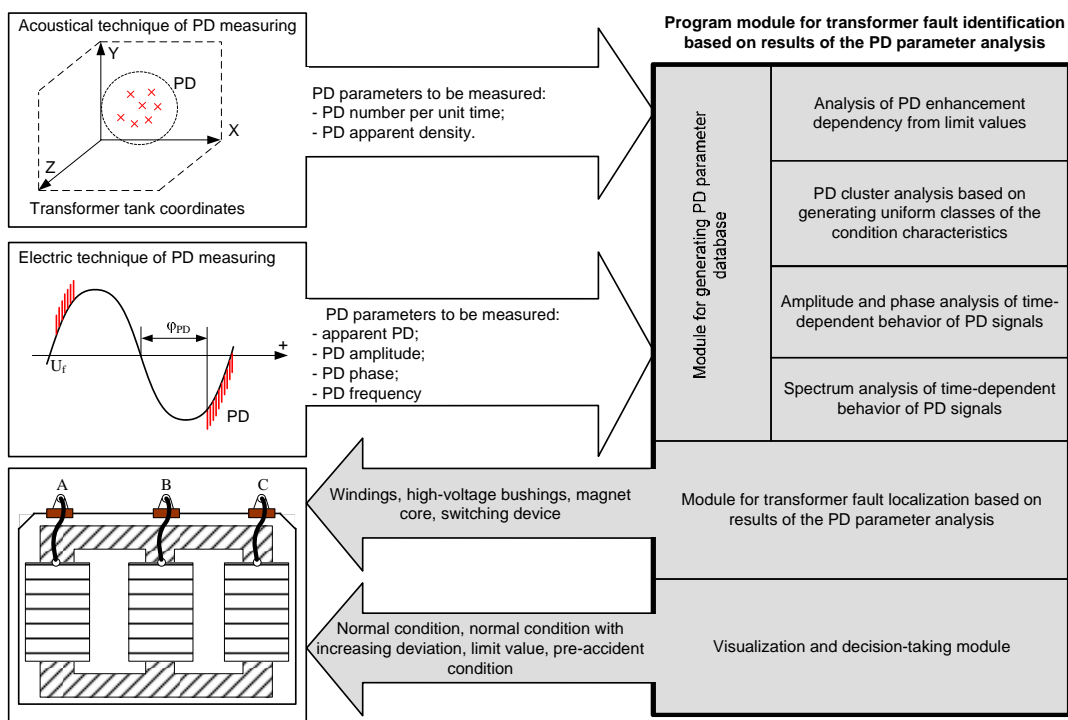


Fig. 1. Functional structure explaining the developed technique of transformer fault identification.

2.1. Experimental research of discharge activity

Within the framework of engineering implementation of the developed technique, acoustic tracing and processing data of partial discharges in the transformer tanks of the power sub-stations of industrial power plants were performed. Measuring was carried out with portable device for PD analysis and tracing defect zones in the insulation of the AR-700 high-voltage facilities [8]. For this, acoustic sensors were installed on the outer sides of the tank. Their location was chosen with methods specified by GOST 20074-83.

Fig. 2 shows intrinsic flow charts obtained at the transformer. Acoustic spikes recorded in pickup signals provided by sensors characterize the PD amplitude, frequency and duration [9].

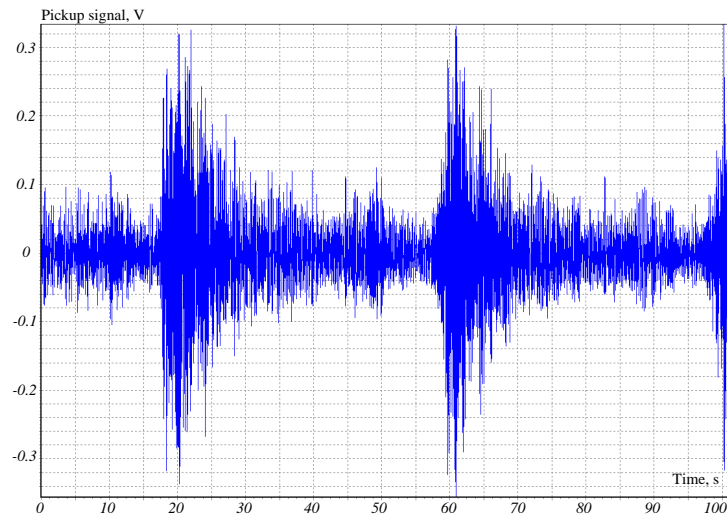


Fig. 2. Acoustic signal oscillographs.

Fig. 3 shows results of PD recording during the set time period. Points outlined within the volumetric tank envelope visualize the number and location of discharges recorded during 1 minute. There are geometrical coordinates of all recorded discharges in the right part of the picture. During experiment at relatively high noise levels (0.45 V), a significant number of discharges distributed practically in the whole tank envelope was recorded. Experiments were carried out at six transformers of the power generating sets.

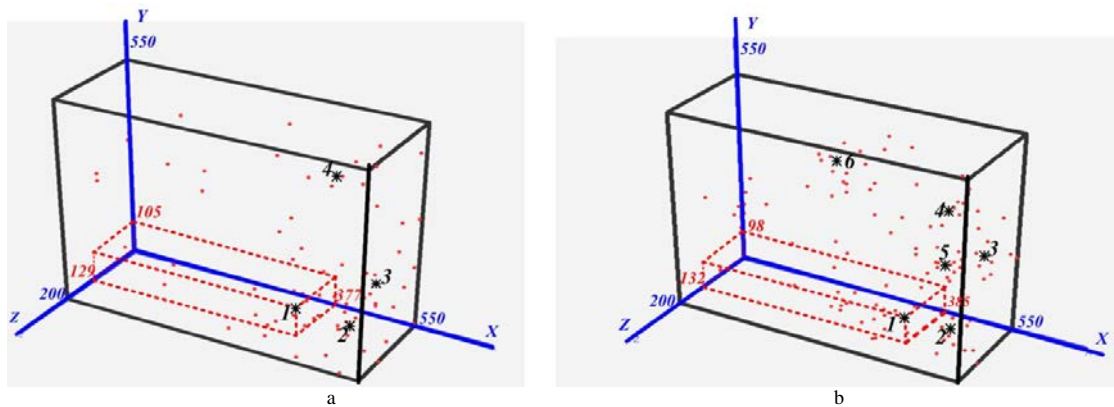


Fig. 3. Three-dimensional circuits of PD distribution in transformer No.5.

For estimation of discharge activity development, three-dimensional PD circuits obtained with measuring results at the margin of 6 months were compared (Fig. 3, a and Fig. 3, b, correspondingly). As a result, it was found out that at later measuring operations an increase of discharge activity can visually be observed; this fact confirms the change of their condition. At this, volume PD distribution in separate tank zones is changed too, thus, reflecting defect growth in these zones.

As may be inferred from the results provided, a large PD location data file may be accumulated at diagnosing transformers with acoustic tracing method. Data file processing is required for diagnostics; here, application of statistic analysis methods is not advisable as it requires a priori knowledge of distribution laws.

2.2. Application of subtractive clustering method

Measuring result processing is proposed to be performed with cluster analysis method enabling division of pooled data under consideration into groups of similar objects (clusters) and record distribution into different groups or segments. Most clustering algorithms may be used under conditions of almost the whole unavailability of information on data distribution laws. Objects with quantitative (numerical), qualitative or mixed attributes are subject to clustering. Division of sampled information into groups of similar objects simplifies further data processing and decision-making as a specific analysis method may be used for each cluster. The clustering algorithm is the α -function: $X \rightarrow Y$ that assigns to all $x \in X$ objects numbers of $y \in Y$ clusters. The Y range is known in advance in some cases but normally the objective is to determine an optimum cluster number in terms of the specified criterion of clustering quality.

Based on the analysis of conceptual theoretical issues of the clustering analysis, the subtractive (mountain) clustering algorithm may reasonably be applied for processing outcome of the PD acoustic tracing; here, each point of the data array is assumed to be a center for a potential cluster. For the later, the objective function-density of other points around the considered one shall be calculated. The algorithm enables formalization of expert estimation of any electric machine condition with data obtained at measuring PDs and tracing its temporal variation trend.

As elements of the observation matrix, the PD coordinates (x_i, y_i, z_i) in the volumetric transformer envelope (see Fig. 3) were proposed to be used immediately. Geometric X -, Y - and Z -coordinates of each PD are stored into AR-700 memory and may be output as numerical arrays for processing with the Fuzzy Logic Toolbox package of the MATLAB system being most convenient for processing experimental data [10-12].

The technique of PD analysis using subtractive clustering has been developed based on studies [13]. It includes the following provisions.

1. As reference parameters we propose the x_{ij}, y_{ij}, z_{ij} PD coordinates recorded during experiments in the tank for all considered transformers. The X_{Tj} observation matrices of dimensions $[nj \times 3]$ are formed:

$$X_{Tj} = \begin{bmatrix} x_{(Tj)1} & y_{(Tj)1} & z_{(Tj)1} \\ x_{(Tj)2} & y_{(Tj)2} & z_{(Tj)2} \\ \dots & \dots & \dots \\ x_{(Tj)nj} & y_{(Tj)nj} & z_{(Tj)nj} \end{bmatrix}, \quad (1)$$

where i and nj – number of the recorded discharge and PD impulses at the frequency level 10 imp./sec. for transformer No. j .

2. Potentials of clusters' n -centers shall be calculated with the following dependence

$$P(Z_h) = \sum_{k=1, M} \exp(-\alpha D(Z_h, X_k)), \quad h = \overline{1, S},$$

where $Z_h = (z_{1,h}, z_{2,h}, \dots, z_{n,h})$ – a potential center of cluster No. h ; $h = 1, S$; α – positive constant; $D(Z_h, X_k)$ – distance between a potential center of the Z_h cluster and X_k clustering object.

3. The potential shall be recalculated with the following dependence

$$P_2(Z_h) = P_1(Z_h) - P_1(V_1) \cdot \exp(-\beta \cdot D(Z_h, V_1)),$$

where $P_1()$, $P_2()$ – potentials at the 1st and 2nd iterations, correspondingly;

V_1 – center of the first detected cluster: $V_1 = \arg_{Z_1, Z_2, \dots, Z_Q} \max(P_1(Z_1), P_1(Z_2), \dots, P_1(Z_Q))$;

β – a positive constant.

Recalculation occurs as long as the rated potential value is higher then the set limit value P_{lim} .

F_{Tj} matrices of detected PD cluster centers are formed for each transformer. They correspond to the first steady-state operation mode:

$$F_{Tj} = \begin{bmatrix} x_{(Tj)1} & y_{(Tj)1} & z_{(Tj)1} \\ x_{(Tj)2} & y_{(Tj)2} & z_{(Tj)2} \\ \dots & \dots & \dots \\ x_{(Tj)Lj} & y_{(Tj)Lj} & z_{(Tj)Lj} \end{bmatrix},$$

where Lj – the number of the PD clusters detected in transformer No. j in the first steady-state on-load operation mode.

Vectors of corresponding cluster potentials $S_{Tj} = [P_{(Tj)1} \ P_{(Tj)2} \ \dots \ P_{(Tj)Lj}]$ are formed separately.

4. When the load mode or temperature of the transformer are changed, that is, additional factors appear that may result in variation of the insulation PD intensity, the X'_{Tj} observation matrices for a new load mode are generated according to (1).

5. Calculations as per sub-s. 2 and 3 of this algorithm are carried out and F'_{Tj} matrices of the detected centers of PD clusters for the altering mode and corresponding S'_{Tj} potential vectors are determined.

6. For each transformer, the M'_j dimension of rows (number of detected clusters) of F'_{Tj} matrices is compared with the M_j dimension of F_{Tj} matrix rows of the previous mode. The number of additionally generated clusters (additional PD sources) $\Delta M_j = M'_j - M_j$ is specified. If $\Delta M_j < 0$ that means a normal condition of the transformer insulation.

7. If $\Delta M_j > 0$ the coordinates of $x_{(Tj)k}$, $y_{(Tj)k}$, $z_{(Tj)k}$ cluster centers and vectors of S_{ATj} potentials of additionally generated PD clusters shall be defined (here, k – number of the cluster generated).

With due regard to the potential values, the hazard rate of recent sources of partial discharges may be estimated while pursuant to cluster center coordinates, the location and so, reasons and mechanism of occurring damage inside the transformer tank are derived.

The schematic algorithm of PD analysis by means of the technique under consideration is provided in Fig. 4. With this algorithm and the Fuzzy Logic Toolbox applications, changing discharge activity of electricity works (EW) transformers has been analyzed. The coordinates of the detected clusters for transformer No. 5 are outlined in Fig. 3 by points with corresponding numbers. For the first measuring (Fig. 3, a), 4 clusters are pronounced, for the second one (Fig. 3, b) – 6. As an example, both figures show plotting the center of cluster No. 1 with coordinates of F_{Tj} , F'_{Tj} matrix rows of the cluster centers.

The coordinates of clusters with the highest intensity established with results of the first measuring and of newly generated clusters carry inference about development of discharge processes near B and C high-voltage phase inputs. The newly generated PD clusters (No. 5 and 6) are determined to have rather high potentials (higher PD density compared to the centers) in comparison with proportional's of clusters recorded during the previous measuring. This conclusion served as a recommendation for operating personnel to continue capturing and processing data with the AR-700 device and additional transformer examinations with other methods.

3. Conclusion

The example provided proves that the developed technique enables comparing discharge focal points (cluster centers) directly with packaging transformer assembly units (windings, high-voltage inputs, RUL etc.), so fault localizing and identifying. It is obsequiously that drawing firm conclusions on condition of the examined transformers based on only two measuring operations may be difficult. However, the obtained results provide an

opportunity to show the application of the proposed algorithm and its efficiency at diagnostics under operational conditions [14].

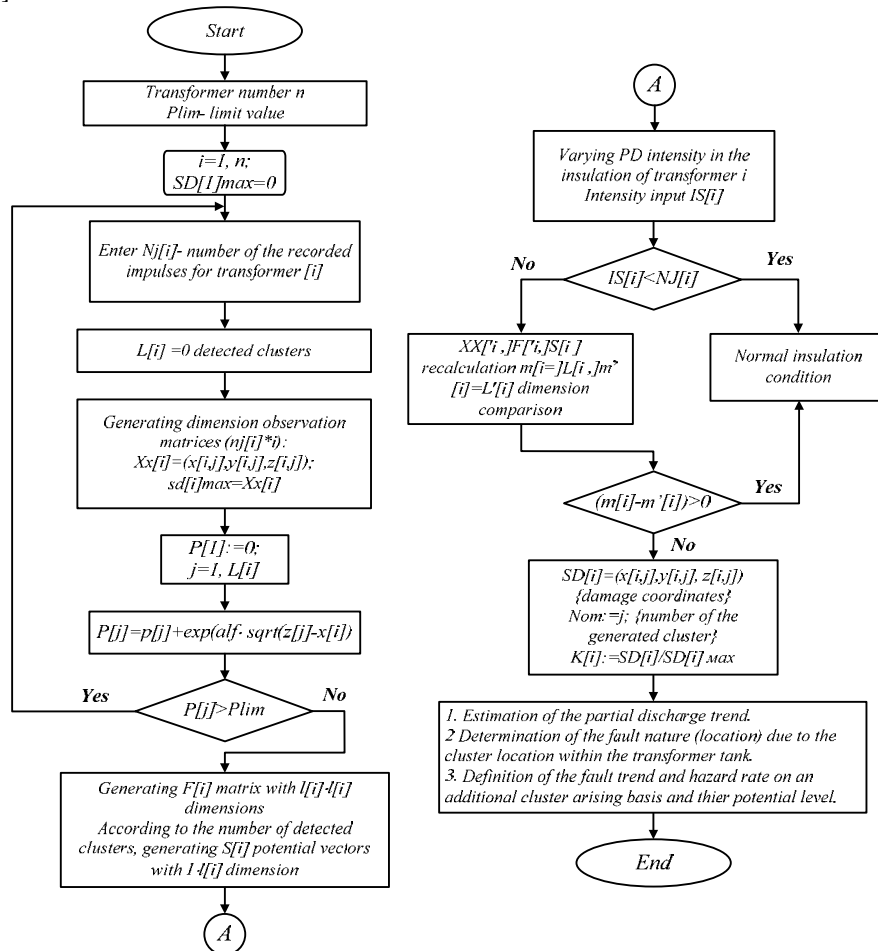


Fig. 4. Algorithm of transformer condition analysis based on the subtractive clustering method.

The key point of the developed technique is the use of two methods of measuring PD parameters – an acoustic and electric one. A simultaneous application of these methods enables:

- significant expansion of the initial PD data base for further analysis and tracing incipient insulation damages;
- application of mathematical analysis methods using as initial data parameter of acoustic radiation and electric generation signals due to partial discharges;
- enhancing fidelity of measuring PD parameters.

The advantage of the developed technique is in possibility to estimate transformer insulation condition timely due to the dynamic examination of discharge processes for a relatively short term. Globally, it ensures more objective estimation of condition of the transformer windings insulation.

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